

Negative chlorine ions from multicusp radio frequency ion source for heavy ion fusion applications

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Use of high mass atomic neutral beams produced from negative ions as drivers for inertial confinement fusion has been suggested recently. Best candidates for the negative ions would be bromine and iodine with sufficiently high mass and electron affinity. These materials require a heated vapor ion source. Chlorine was selected for initial testing because it has similar electron affinity to those of bromine and iodine, and is available in gaseous form. An experiment was set up by the Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory to measure achievable current densities and other beam parameters by using a rf driven multicusp ion source [K. N. Leung, *Rev. Sci. Instrum.* **65**, 1165 (1994); Q. Ji *et al.*, *Rev. Sci. Instrum.* **73**, 822 (2002)]. Current density of 45 mA/cm² was achieved with 99.5% of the beam as atomic negative chlorine at 2.2 kW of rf power. An electron to negative ion ratio as low as 7 to 1 was observed, while the ratio of positive and negative chlorine ion currents was 1.3. This in addition to the fact that the front plate biasing had almost no effect to the negative chlorine ion and electron currents indicates that a very high percentage of the negative charge in the extraction area of the ion source was in form of Cl⁻ ions. A comparison of positive and negative chlorine ion temperatures was conducted with the pepper pot emittance measurement technique and very similar transverse temperature values were obtained for positive and negative chlorine ions. © 2003 American Institute of Physics. [DOI: 10.1063/1.1571973]

I. MOTIVATION FOR THE EXPERIMENT

Neutral heavy atoms produced from negative ions have been proposed as drivers for inertial confinement fusion.^{1–3} The best candidates for these ions seem to be⁴ bromine (mass 81, electron affinity 3.63 eV) and iodine (mass 127, electron affinity 3.06 eV). These elements have to be heated to a vapor, and the ion source would have to be operated at elevated temperatures to prevent the condensation of the vapor on cold surfaces. For an initial estimate of achievable negative ion current densities from bromine and iodine, chlorine was used because it has a very similar electron affinity (3.61 eV). It is readily available in gaseous form, which enables the test to be carried out using an already existing ion source by just modifying the gas lines to be compliant with corrosive gases.

II. EXPERIMENTAL SETUP

The negative chlorine ion production experiment was conducted in Lawrence Berkeley National Laboratory's Plasma and Ion Source Technology Group. In Fig. 1, a schematic diagram of the set up is presented. A 15 cm long by 10 cm diam multicusp type source chamber with 20 cusp lines was used. A movable magnetic dipole filter with 135 G peak field and full width at half maximum of 2.4 cm was installed

through the back plate of the source. This filter separates the ion source into a discharge and an extraction region. A 12.56 MHz, 2.2 kW rf power supply with accompanying matching network and a quartz coated rf antenna were used in the tests. The rf power supply and the matching network were floated at high voltage to enable proper shielding of the antenna legs in order to reduce the rf noise. The negative ion extractor and the Faraday cup were designed and optimized for a 10–20 kV extraction voltage range. The first part of the extractor is a high voltage plasma electrode with a single aperture. It is

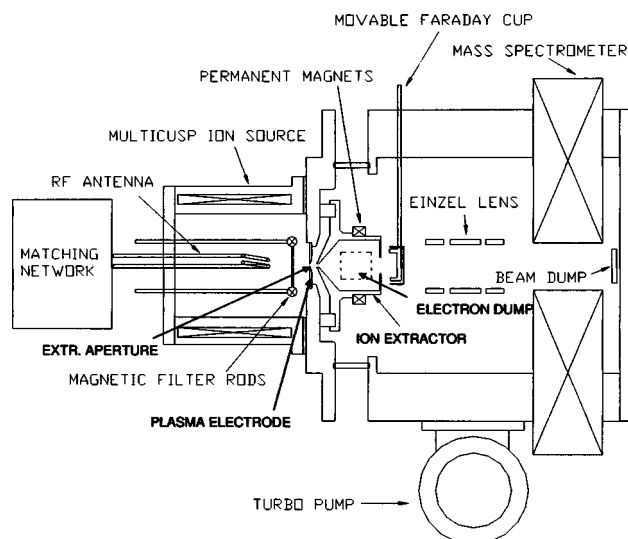


FIG. 1. Schematic of the setup.

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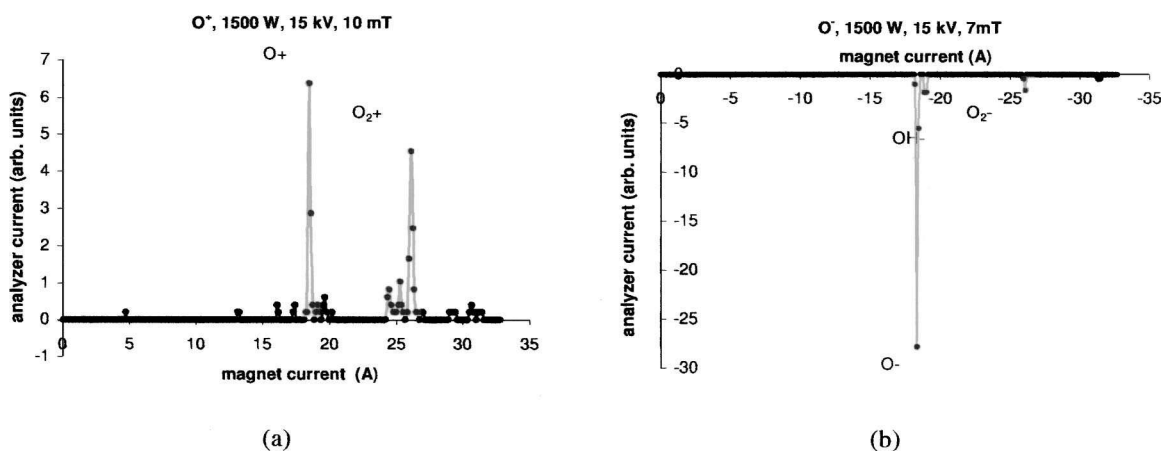


FIG. 2. (a) O^- , O^+ , and electron currents as a function of the extraction voltage, (b) O^- current as a function of the source pressure and rf power.

insulated from the ion source body to enable biasing of the plasma electrode relative to the ion source. Ions are extracted by a water cooled, grounded ion extractor with permanent magnets attached to it for the removal of electrons from the ion beam. A movable, secondary-electron-suppressed Faraday cup was installed for the ion beam current measurement. An einzel lens matches the ion beam to a magnetic mass spectrometer, which is used to analyze the extracted ion species. A 500 l/s turbomolecular pump is installed in the extraction chamber. A smaller 150 l/s turbo pumps the volume of the magnetic mass spectrometer. Chlorine gas was fed to the ion source through a gas line constructed from stainless steel, and the ion source and the gas line were located inside a ventilated hood to prevent any escape of chlorine gas. No cesium or other additives were introduced into the plasma chamber in any of the measurements.

III. MEASUREMENTS WITH OXYGEN

The experimental setup was tested first with an oxygen plasma. Positive and negative ion beams were extracted and

analyzed to make sure the setup worked for both polarities. It was noticed that the electron beam focused into a small spot on the electron dump and started melting it. The water cooling of the electron dump was improved, after which the extraction worked well. Current density, defined by dividing the measured Faraday cup ion current with the extraction aperture area, of 5.7 mA/cm² for O^- and 22 mA/cm² for O^+ was measured at 2.0 kW of rf power. The electron-to-ion ratio was 300. In Fig. 2(a) the measured positive and negative atomic oxygen ion current and the electron current are plotted as a function of extraction voltage at 1.5 kW of rf power and 10 mTorr of source pressure. For Fig. 2(b) the measured atomic negative oxygen current is plotted as a function of source pressure and rf power. The extraction aperture diameter and the extraction gap were 1.5 and 5.5 mm, respectively. The ratio of the O^+ and O^- current densities was 4. At 1.5 kW of rf input power, 40% of the ions were O^+ in the positive beam and 90% were O^- in the negative beam. Positive and negative oxygen spectrums are presented in Fig. 3.

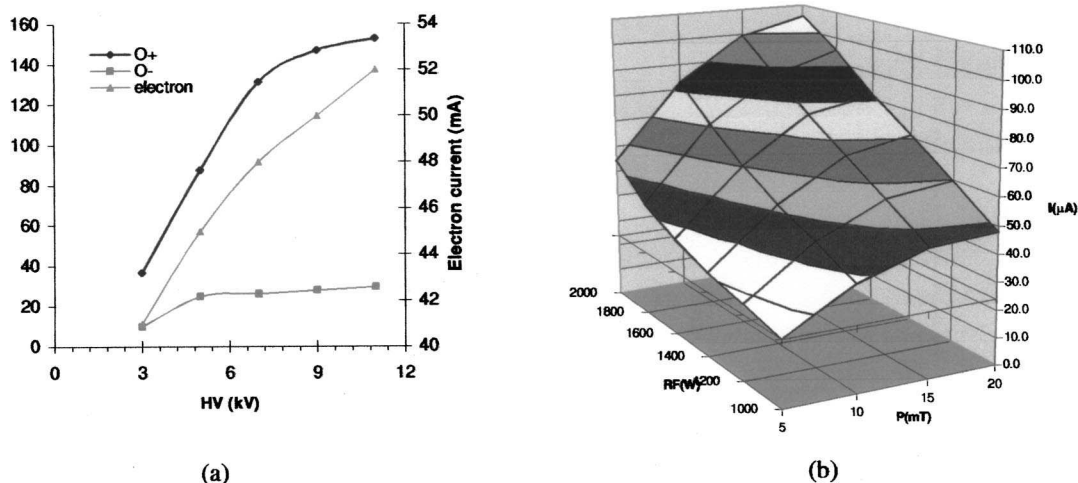


FIG. 3. (a) Positive and (b) negative oxygen spectrums.

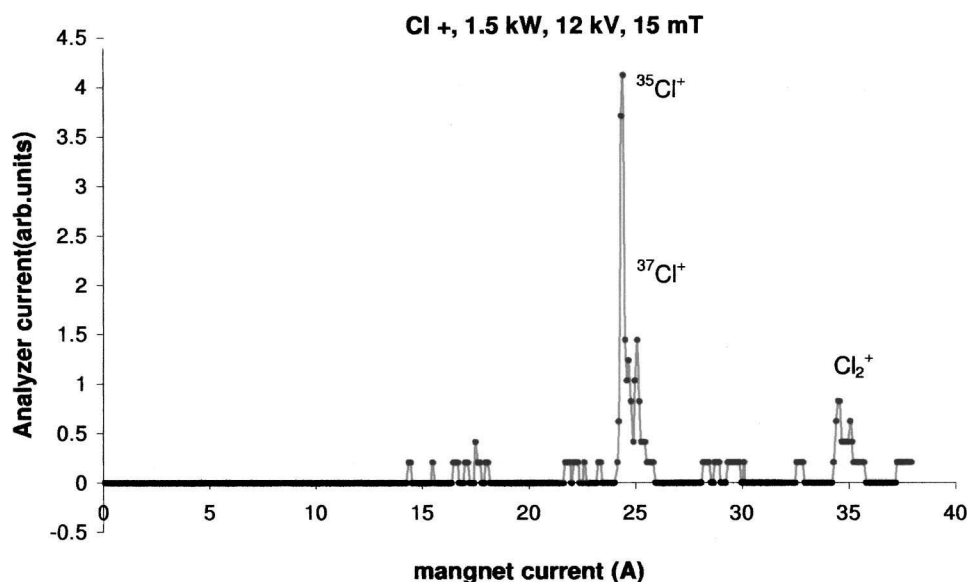


FIG. 4. Positive chlorine ion spectrum.

IV. MEASUREMENTS WITH CHLORINE

After testing the system with oxygen, chlorine operation was started. A positive chlorine ion spectrum is presented in Fig. 4. Some impurities can be seen in the spectrum, mainly nitrogen and oxygen. About 82% of the beam was atomic chlorine ions. The initial tests were carried out with a 1.5 loop transverse quartz antenna with the tip of the antenna 35 mm away from the filter rod center plane. The filter rods were 13 mm from the plasma electrode. This was the same set-up which was used for oxygen measurements. A negative chlorine ion spectrum with the same rf power can be seen in Fig. 5. The spectrum is noticeably clean, as 99.5% of the beam is atomic Cl^- , with the two peaks corresponding to the 76% and 24% natural abundance of chlorine isotopes 35 and 37, respectively. Only about 0.5% of the beam is molecular Cl_2^- ions.

In Fig. 6(a), the measured Cl^- and Cl^+ ion currents and the electron current are plotted as a function of extraction voltage at 1.0 kW of rf power and 25 mTorr of source pressure. Cl^- and Cl^+ ion currents saturate at 7 and 13 kV, respectively. The higher saturation voltage of Cl^+ is due in part to the higher total positive ion density at the extraction

region of the plasma chamber. In Fig. 6(b) the Cl^- current density is plotted as a function of rf power and source pressure. The data were taken with a 2 mm extraction aperture and a 4.5 mm extraction gap. The Cl^- current density has a maximum at 30 mTorr source pressure, and increases linearly with rf power. The maximum achieved current density of 45 mA/cm² was measured at 2.2 kW of rf power and 28 mTorr source pressure.

Biasing of the front plate has been reported in the literature to increase the negative ion yield and to reduce the electron yield from volume plasma source.⁵ With oxygen this effect was clear. The O^- ion current increased by 20% and the electron current decreased by 25% when the front plate voltage was increased from 0 to 15 V. With higher voltages the ion current started to go down while the electron current also continued decreasing. With chlorine this effect was much smaller. When the front plate was biased from 0 to 35 V, the Cl^- current hardly changed, and the electron current decreased by less than 5%. This is probably due to the fact that most of the negative charge in the extraction region of the ion source is chlorine ions and only a few percent are electrons. Figures 7(a) and 7(b) show the measured negative ion and electron currents as a function of front plate bias for oxygen and chlorine.

The effects of ion source chamber pressure and filter magnet position on the extractable negative chlorine and electron currents can be seen in Figs. 8(a) and 8(b). Electron current goes down from 74 to 16 mA when the source pressure was increased from 15 to 30 mTorr. The ion current increased from 0.95 mA at 15 mTorr to 1.05 mA at 25 mTorr, and started to decrease at higher pressures. When the magnetic filter rods were moved from 11 to 21 mm away from the plasma electrode, the ion current went down from 0.8 to 0.6 mA, while the electron current had a minimum of 8.8 mA at 16 mm. The data in Fig. 8 were taken with a 2 mm extraction aperture and 2.0 kW of rf power for Fig. 8(a) and 1.5 kW and 30 mTorr of source pressure for Fig. 8(b).

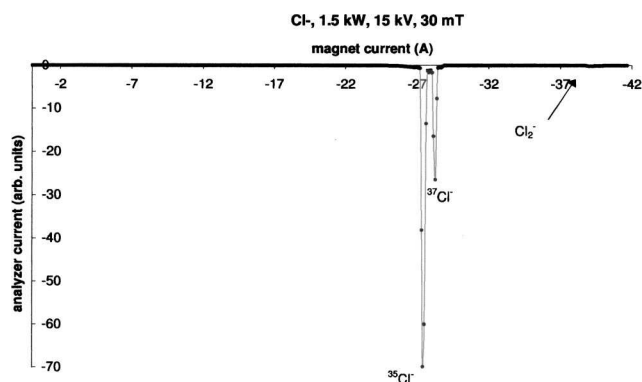


FIG. 5. Negative chlorine ion spectrum.

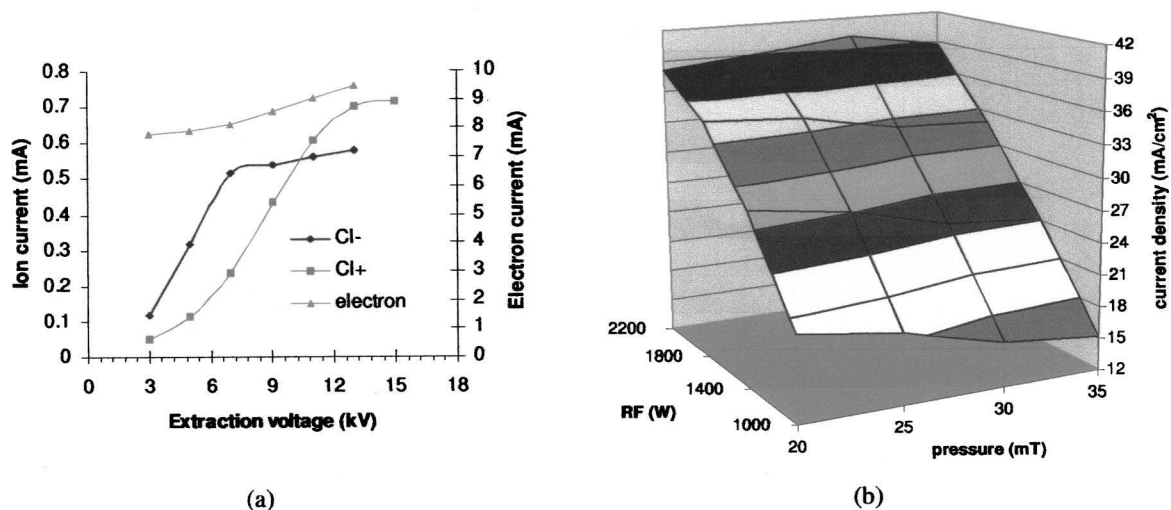


FIG. 6. (a) Cl⁻, Cl⁺, and electron currents as a function of the extraction voltage and (b) Cl⁻ current as a function of the source pressure and rf power.

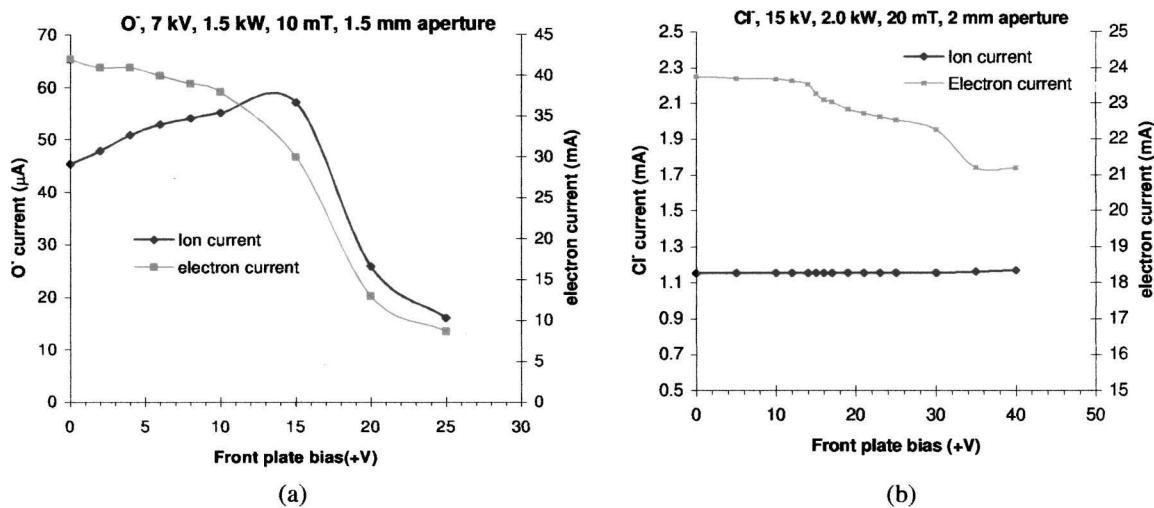


FIG. 7. Effect of the front plate bias voltage on negative ion and electron currents for (a) oxygen and (b) chlorine.

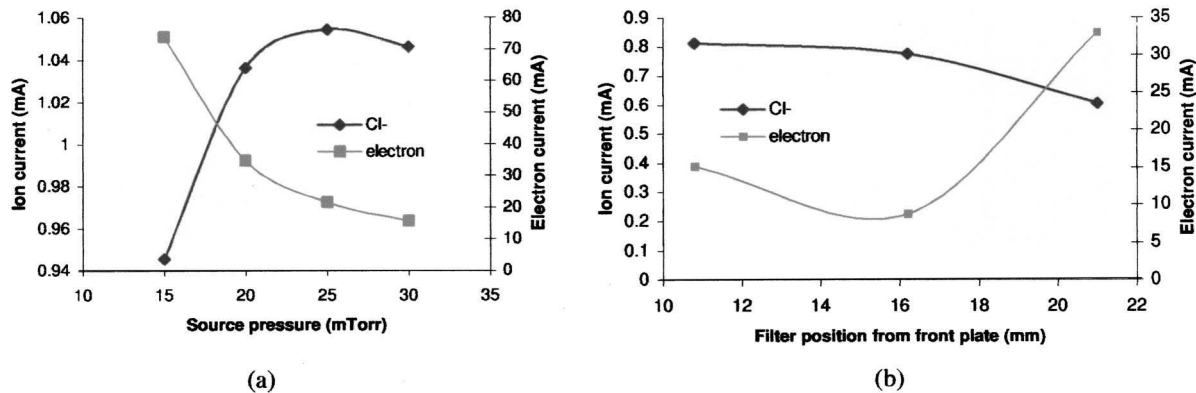


FIG. 8. Negative chlorine and electron currents as a function of (a) source pressure and (b) magnetic filter position.

The transverse temperatures of the positive and negative chlorine ions were determined by a pepper pot measurement. The ion beam was shot through a mask with 0.2 mm holes to a target foil. Transverse temperature of the beam was determined from the marks in the foil in parallel and transverse directions to the electron filter magnetic field. The exposures were done using 1.5 kW of rf power and 30 mTorr of source pressure for both positive and negative chlorine ions. The temperatures measured in the parallel and transverse directions to the magnetic field for the negative chlorine were 0.3 and 0.5 eV, respectively. For positive chlorine the temperatures were 0.2 and 0.5 eV. The ion temperature is larger in the transverse direction as the magnetic field deflects the ions. The relatively bigger temperature in the direction trans-

verse to the magnetic field for positive chlorine can be explained by the large molecular chlorine ion component in the positive beam.

ACKNOWLEDGMENT

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¹K. N. Leung, Rev. Sci. Instrum. **65**, 1165 (1994).

²Q. Ji, T. J. King, K. N. Leung, and S. B. Wilde, Rev. Sci. Instrum. **73**, 822 (2002).

³L. R. Grisham, Nucl. Instrum. Methods Phys. Res. A **464**, 315 (2001).

⁴L. R. Grisham, Fusion Sci. Technol (to be published).

⁵K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. **56**, 2097 (1985).